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The Use of a Magnetic Field to Measure Particle Velocity
I. Basic Concepts and Exploratory Experiments

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I. Basic Concepts and Exploratory Experiments

by

J. N. Fritz
R. S. Caird
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THE USE OF A MAGNETIC FIELD TO MEASURE PARTICLE VELOCITY
I. BASIC CONCEPTS AND EXPLORATORY EXPERIMENTS

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ABSTRACT

Some of the initial effort of Group GMX-6, Los Alamos Scientific Laboratory, in using magnetic fields to measure particle velocities is described. Two types of probes, the U-probe (or Zavoiskii technique) and an axially symmetric probe, are discussed. Some of the preliminary results indicating the possibilities of the techniques are presented and directions for future work are indicated.

I. INTRODUCTION

Several years ago the direct measurement of material, or particle velocity inside shock-loaded materials was considered impossible. Early efforts to measure a Hugoniot curve for equation-of-state purposes were achieved indirectly by Walsh and Christian[1] through the measurement of free-surface velocity and shock-wave velocity over a finite interval. In addition to the requirement that the free-surface velocity measurements be reduced to a particle velocity, the finite interval used to measure the free-surface velocity prevented observation of any structure that might have been present in the emerging wave. By using projectiles moving with a known velocity, the particle velocity behind the shock wave after impact is readily determined by satisfying the Hugoniot relationships in the pressure particle-velocity plane. This feature has been used extensively in various gun devices and also in high-explosive-driven metal plate experiments where minor corrections are required to correct for the previous shock heating. As valuable as this technique is, no information is obtained about the detailed structure of the shock wave.

Early attempts (1960) to resolve the shock-wave structure in solids resulted in three workable techniques; an optical lever arm, a dc capacitor technique, and the quartz gauge. Of these three techniques the capacitor and quartz gauge are still extensively used. In the dc capacitor technique developed by Rice,[2] a conducting free surface forms an integral part of a capacitor. The resulting dependence of the capacitance on the position of the free surface is transformed by appropriate circuitry into a signal that is essentially proportional to the velocity of the free surface. The quartz transducer developed by Jones et al.[3] utilizes the piezoelectric effect in single quartz crystals to record the stress level at a quartz-material interface. This latter technique is limited to pressures below that at which the single quartz crystal is destroyed. Both of these techniques have found their primary application in studying elastic-plastic flow at lower pressures.

Because of the limitations imposed by these techniques, efforts to devise different and hopefully better methods of measuring the mass velocity have continued. The laser interferometer,[4] although basically a device to measure free-surface velocity, can measure the velocity behind the shock wave when transparent materials are employed. The manganin wire gauge (Bernstein and Keough[5]) is also being used extensively. Photoetched elements whose total thickness is only about 0.05 mm are commercially available and have removed some of the assembly difficulties.

Dremin et al.[6] and Al'tshuler et al.[7] have used an embedded circuit loop and a magnetic field parallel to the shock front. They attribute this technique originally to Zavoiskii. This method has been used more recently by Petersen et al.[8] As the segment of the circuit parallel to the shock front is picked up and given the particle velocity behind the shock by the wave front, it "cuts" the lines of the magnetic field and generates an electromotive force proportional to the particle velocity. Such a system is appealing because only the length of the moving circuit segment and the tangential magnetic field are needed to give a direct measurement of the particle velocity. However, such an arrangement is complicated by embedding the pick-up loop in the material to be studied as well as obtaining a uniform tangential magnetic field unperturbed by motion of conducting surfaces in the vicinity of a shocked sample. Results of some exploratory experiments performed by LASL Group GMX-6 with this technique are described in the next section.

A different approach to measuring particle velocities by utilizing magnetic fields is given here. This technique makes use of the change in curvature of flux lines locked into the surface of moving conductors. Experiments using several modifications of this system have been made. This technique appears to be the most versatile because it is capable of resolving the motion of embedded conducting foils in nonconductors, including high explosives, without the associated problem of bringing electrical contacts out of the samples. This technique can also be used to study the free-surface motion of shock-loaded conductors. These experiments are described and some of the results are presented in Sec. III.

II. FEASIBILITY EXPERIMENTS UTILIZING THE TRANSVERSE MAGNETIC FIELD AND U-PROBE

In our initial efforts to gain experience with the Zavoiskii technique, we employed HE driver systems and small expendable magnets to generate the field. A pair of bar magnets, taped together, was mounted on each side of the sample. This simple arrangement produced a transverse field through the U-probe that was reasonably uniform over the area to be swept over by the bottom leg of the probe during the experiment (Fig. 1). The B field, measured by a permanent magnet gaussmeter, ranged from 0.3 to 1.5 kG in these experiments. Materials investigated were Lucite, alumina ceramics, and fused silica, chosen because of immediate availability and ease of fabrication. Typically, three 1/2-in.-wide bars were mounted on a 1 1/2-in. plate using Epocast 202 or Eastman 910 as a binder. In spite of its high density, platinum was used to make the loop because of the quality and thickness (0.1 to 0.5 mil) of some available platinum foil. The length of the transverse segment (ℓ of Fig. 1) was ~ 0.5 in. in all these experiments. The $\underline{v} \times \underline{B}$ expression for the electric field then leads to the sensitivity function: V (volts)/u_p (mm/μsec) = B (gauss)/787.

Although 15 experiments were performed in this phase of the program, only five will be discussed because these illustrate some of the

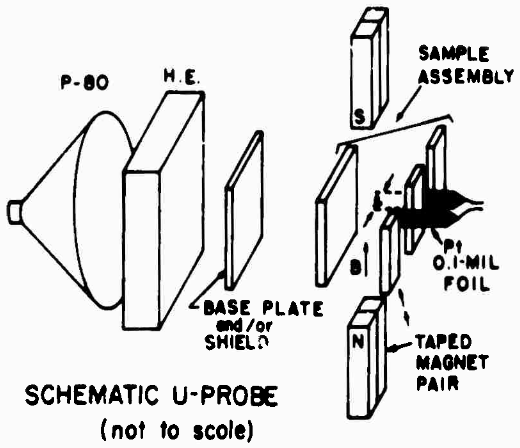


Fig. 1. An exploded view of a U-probe experimental assembly. Two taped pairs of bar magnets supply the transverse field through the conducting loop. The base of the sample and the three blocks holding the conducting loop are usually constructed of the sample material. The critical dimension, ℓ, is indicated on the figure. The base plate can be of the same material as the sample, or some other material whose purpose is to modify the pressure pulse produced by the explosive or to shield the B field from the effect of the moving explosive.

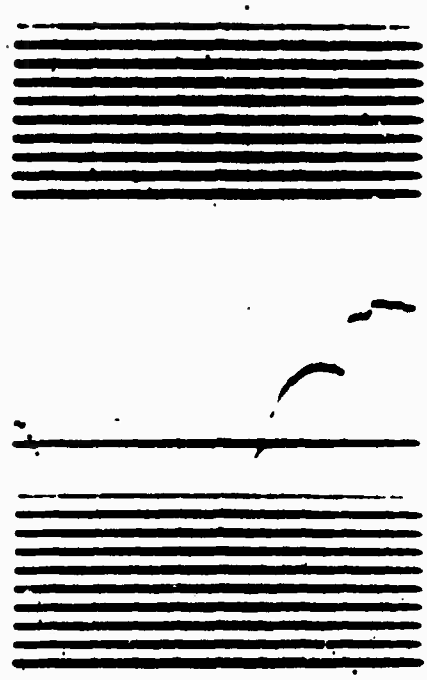


Fig. 2. U-probe record of an alumina ceramic being driven by a TNT/2024 aluminum driving system in a B field of 540 G. Calibration grid has 0.5 μsec time marks and 0.2 voltage spacing with a negative 0.2-V base line.

problems associated with this technique. This technique has the potential of observing details in complicated shock-wave structure.

The first two experiments in the series employed an 8-in. plane wave lens (P-80); 2 in. of TNT, and a 1/4-in.-thick 2024 aluminum base plate. The first experiment had a Plexiglas sample and the second one had an alumina-silica ceramic sample. Both records (the second is reproduced in Fig. 2) showed an initial negative voltage sweep undoubtedly caused by the motion of the 2024 aluminum base plate forcing the lines of flux through the U-probe opposite to the way the bottom of the probe would be traversing the field if it were moving in the same direction as the base plate. The magnitude and time variation of this effect are, to all practical purposes, impossible to ascertain. The reflected shock produced at the 2024 aluminum-ceramic interface apparently has, toward the end of the record, slowed the aluminum sufficiently so that there is some semblance of a base-line before the probe starts to move. The increase in voltage from this level to the flat part of the wave is compatible with a particle velocity, 1.2 mm/μsec, that would be expected with this particular explosive system. The record shows evidence of a two-wave structure probably due to the quartz in the ceramic.

Figure 3 is a reproduction of the trace obtained with alumina-silica ceramic driven by a 4-in.-thick charge of baratol. There were no metal plates in this experiment and although there is some noise from the HE, this record is considerably cleaner than the previous experiment. The two-wave structure exhibited here is believed to be due to the elastic-plastic transition. The

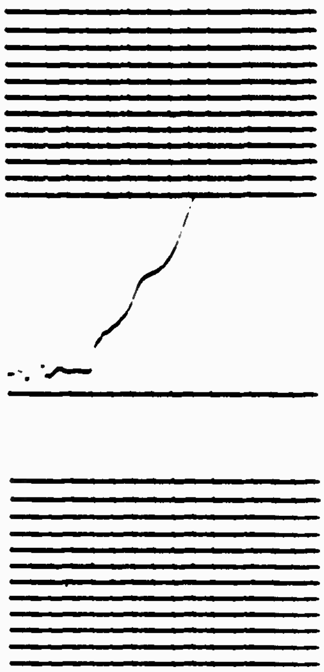


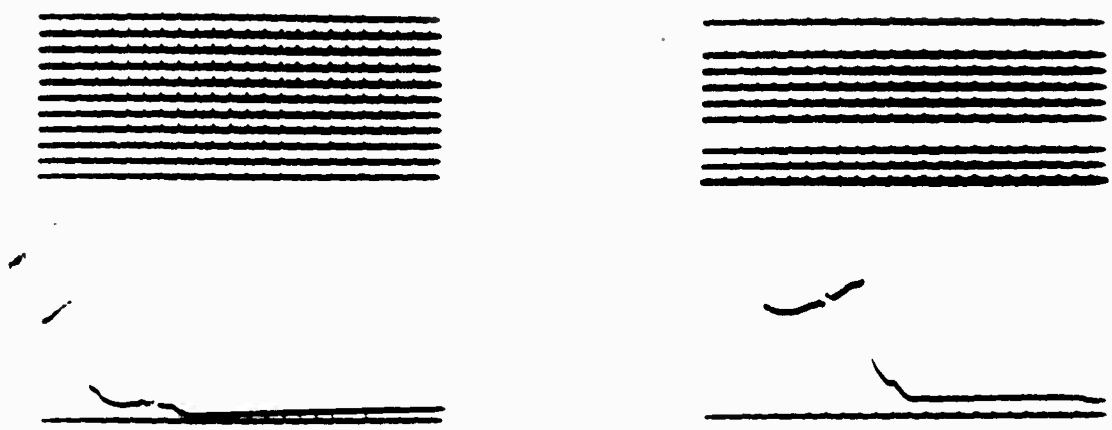
Fig. 3. U-probe record for alumina-silica ceramic driven by 4-in. baratol. The grid has 0.2-μsec time marks and 0.15-V spacing. The foil was located 0.3 in. from the HE-ceramic interface with a 0.2 in. covering of the ceramic. The B field was ~ 1100 G.

amplitude of the top of the second wave corresponds to a velocity that is slightly less than 0.7 mm/μsec.

Early motion of the field through the area enclosed by the U-probe can be solved in two ways. The geometry can be arranged so that even if motion of metal plates or other conductors does disturb the field, as much flux enters the area of the probe as leaves it. The alternative is to confine the B field to a small region that contains no moving conductors other than the probe during the time of measurement. From their published work, one can infer that the Russian workers have probably used both methods to eliminate this early signal. Al'tshuler et al.[7] used a thick copper (≥ 1 cm) driver in close proximity to the sample. To eliminate the negative early signal in such an arrangement, the entire volume of the experiment must be in a homogeneous field. Although the flux initially in the copper remains trapped in the metal, and the field in front of the copper is changing with time, the flux enclosed in the U-probe will not change and there will be no unwanted early signal if the field is homogeneous both in front of and in back of the driver plate, and if the lines of the field are anchored far away from the experiment. Extensive experimentation using such a technique could be done economically by using a large reusable shielded electromagnet to create a large field volume in which to conduct the experiments.

Dremin et al.,[6] although they probably used the large field volume available to them, used paraffin as a base plate. The paraffin, while limiting the pressure attainable in certain samples, does serve to keep moving conductors farther from the sample and also apparently shields the U-probe from noise generated by the HE. This shielding may be accomplished by having the HE completely reacted before the probe moves. Two experiments, whose traces are shown in Fig. 4, show the effect of (a) removing the 2024 driver, and (b) replacing it with a layer of paraffin. Both assemblies had a P-80, 2 in. of baratol, and a platinum foil embedded between two layers of 1/4-in. fused silica. The B fields were 750 and 800 G, respectively. The initial negative voltage, although much diminished from that created by a metal driver, is still present in (a), above, is probably caused by the detonation wave moving through the HE, and is effectively stopped when the wave reaches the quartz sample. Spacing the sample away from the HE with paraffin displaces the negative sweep while leaving the record due to the foil motion essentially unchanged. The effect of the arrival of the detonator wave at the paraffin-HE interface can be seen at the far right of the second record (Fig. 4).

Wackerle,[9] used precision optical reflection experiments to study the free-surface motion of shock-loaded fused quartz, and differentiated



(a) (b)

Fig. 4. U-probe records of fused silica on baratol. Time increases to the left. The (b) trace differs from (a) in that in the (b) experiment a layer of paraffin was between the silica and baratol. (0.2 μsec, 0.15 V grids with -0.15 V base line).

the resulting x-t curves to obtain the free-surface velocity curves shown in Fig. 5. All these experiments show a ramping precursor whose initial motion moves with a velocity corresponding to the longitudinal elastic wave velocity of 5.97 km/sec. There is ample evidence that an additional two-wave structure exists and, based on the free-surface approximation, Wackerle concludes that this corresponds to a pressure of 96 to 102 kbar. The particle velocities indicated by the voltage signals shown in Fig. 4 are 1.08 mm/μsec for both experiments. These are about 25% greater than implied from Wackerle's data. This discrepancy could be due to the fact that the magnetic probe examines the true shape of the wave 0.25 in. away from its initiation, whereas Wackerle observed the free-surface velocity at the 0.5-in level after it was modified by elastic rarefactions propagating back in from the free surface. The (b) trace in Fig. 4 decays to a constant particle velocity of 0.82 mm/μsec (in reasonable agreement with Wackerle's maximum u_p for the plastic I wave) before the sharp increase in particle velocity from the rarefaction wave arrives at the transverse leg of the U-probe. These observations suggest that we are observing an initially overdriven wave that decays as it runs to a pressure that will not drive the transformation. The Taylor wave in the baratol would lead to decay following the peak pressure, but this cannot explain the overdriven pressure of the plastic I wave. This decay takes about 0.8 μsec and it would seem that some vestige of this wave should reach the free surface. Wackerle did not observe this decay, therefore, perhaps the elastic interaction was effective in eliminating the remainder, if any, of the peaked transient wave. However, the most likely cause of the disagreement both in character

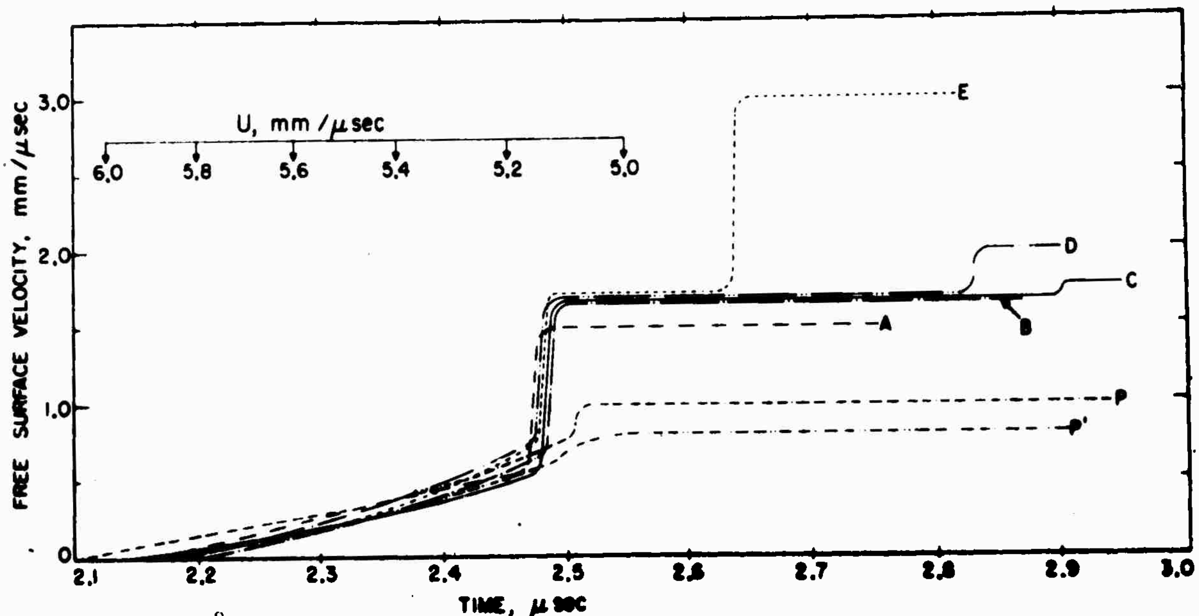


Fig. 5. Wackerle's[9] free-surface velocity profiles for 1/2-in.-thick fused-silica samples. The velocity scale in the upper left of the figure refers simply to thickness of sample divided by arrival time of a particular portion of the profile. Capital letters refer to driver systems used by Wackerle. Of interest are the systems used for B: 2-in. baratol + 1/2-in. 2024 base plate, C: 4-in. TNT + 1/2-in. brass + 1/2-in. 2024, D: 4-in. TNT + 1/2-in. 2024, and E: 4-in. Composition B + 1/2-in. 2024.

and amplitude is probably due to inadequate mapping of the magnetic field.

Both of the traces in Fig. 4 show a previously unobserved structure in the precursor wave. If we apply the jump conditions to the beginning of the small plateau in this wave, we obtain a state of $P = 17$ kbar and $\rho = 2.26$ g/cm^3 for the fused silica. One can only speculate on the reason for this discontinuity. A first thought is that it is a hydrodynamic perturbation in the flow introduced by the platinum foil. However, 10 reverberations through the foil occupy a time of only 14 nsec, while the plateau is 100 nsec in duration. The possibility that this plateau is a gremlin in the record is considerably reduced because it appeared distinctly in two different experiments.

No planned fiducials were put on these records, so an accurate determination of wave velocities was not possible. If one assumes that the leading portion of the elastic precursor traveled with longitudinal wave velocity in fused silica (5.97 mm/μsec), then the plastic I wave traveled with a velocity of 5.0 mm/μsec, in reasonable agreement with Wackerle (5.20 mm/μsec).[9]

Figure 6 shows the particle velocity history at the 0.437-in. level. The elastic precursor does not show the structure exhibited in the previous figures and occupies half the time interval it should, based on velocities of 5.97 and 5.2 mm/μsec for the leading elastic and plastic I waves, respectively. The plastic I wave has a particle velocity of about 0.75 mm/μsec, still less than Wackerle's 0.86 value, again supporting the belief that the magnetic field was not properly calibrated. The next rise, about doubling the particle velocity, is at the right time for the rarefaction to come back through the thin layer of fused silica covering the foil. The simplicity of this record is in accord with that expected from previous experience.

A legible record was obtained on 4 in. of TNT with a sample assembly formed from two layers of fused silica 1/4 in. thick. Although marred by a negative sweep from flux compression and an unexplained negative disturbance before the

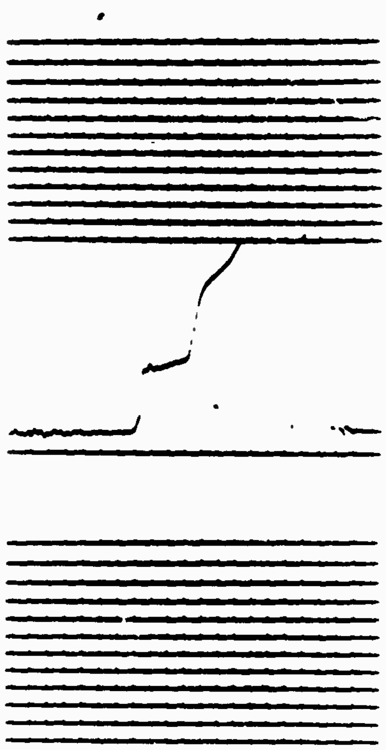


Fig. 6. U-probe of fused silica on 4-in. baratol. The platinum foil was at the 0.437-in. level in the fused silica and there was an additional thickness of 0.124 in. on top of the foil. The field was 800 G and the grid has divisions of 0.2 μsec and 0.2 V. There is a -0.2-V base line under the signal.

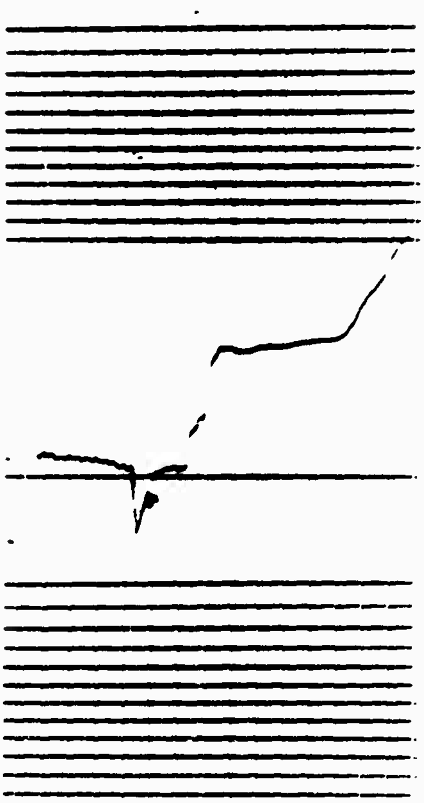


Fig. 7. U-probe of fused silica on 4-in. TNT. The platinum foil was at the 0.255-in. level and the additional top layer was 0.255 in. thick, also. The field was 950 G and the grid had divisions of 0.2 μsec and 0.3 V. There is a -0.3-V base line under the signal.

actual signal, the remainder of the signal could be interpreted as an elastic precursor followed by a two-wave structure. The rise in the last part of the signal is about right for the rarefaction from the free surface. This trace is shown in Fig. 7.

Several conclusions may be drawn from this preliminary experiment with the U-probe.

A. To achieve clean and interpretable signals, variations of magnetic field in the U-probe due to early motion of conducting media must be prevented. This can be achieved by flooding the entire experiment with a large volume uniform field, so that although flux lines are moved early, there is no net change in flux through the U-probe. Or, the experiment can be arranged so that no moving conductors perturb the field until after the probe has made its measurements. To do the former, a permanent reusable arrangement, set up at some capital cost, would be the most economical means of doing relatively large amounts of data production.

B. If small expendable magnets are used, a means of measuring accurately the spatial variation of the transverse B field in the region occupied by the U-probe must be devised to obtain a precise conversion of the voltage signal to particle velocity.

C. Some means for putting a fiducial time mark on the record to indicate initial arrival of the wave at the sample-shield interface would be valuable in measuring wave velocities in the sample. Some way of doing this without unduly complicating sample assembly should be devised.

D. The U-probe offers, through a physical law unclouded by any serious approximation, a method of measuring particle velocity within an insulator. The particle velocity is not confused initially by any interaction coming in from the front free surface. The signal is valid until the wave emerges at the free surface, a time easily identified on the record, and even then the probe apparently continues to function in a respectable manner in most cases.

E. These initial studies indicate the possibility of studying complicated shock-wave structures heretofore inaccessible to measurement. Studies of, and with, the U-probe should continue.

III. THE AXIALLY SYMMETRIC PROBE: INITIAL EXPERIMENTS

The axial probe makes use of the change in curvature of flux lines locked into the surfaces of moving conductors. The basic idea is illustrated in Fig. 8. As a conducting surface picks up a particle velocity from a wave, the points where the flux lines are pinned move down and change the curvature of the magnetic field lines. This results in a change of flux through a test loop and this then produces a signal that is related to the velocity of the conducting surface. Although the figure is drawn as though the lines were perfectly pinned, and as though the flux through the source coil were constant, this is not the case in practice. In fact, the simple arrangement pictured in Fig. 8 would excite oscillations in the L-C circuit formed by the inductance of the source coil and its distributed capacitance. This effect can be eliminated by inserting a conducting shield between the source coil and the rest of the experimental geometry. The shield needs to be a poor conductor on the time scale required to build up the field and a good conductor on the time scale of the measured hydrodynamic flows. This requirement is easy to meet. Alternatively, permanent magnets can be used as the source of the B field. The conductivity of the moving surface is finite and the lines of flux diffuse, but this can be taken into account. The

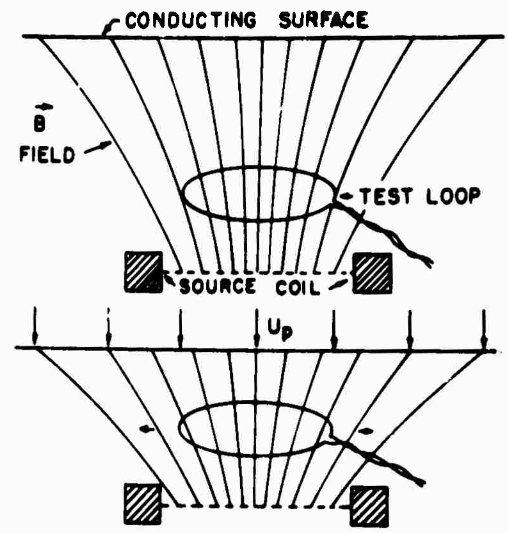


Fig. 8. Basic mechanism of the axial probe. The lines of force, pinned to a foil or a conducting surface, are compressed. The resulting decrease in flux in the test loop causes an emf related to the velocity of the foil to appear on the external leads.

sensitivity of the method depends on the gradient of the component of the magnetic field normal to the conducting surface at the surface, or equivalently, the radial component of the field at the surface. There are a large number of possible configurations and various optimum arrangements for different purposes can be found.

The conducting surface can be a free metal surface, metal surface beneath an insulator, or a thin metal foil sandwiched between insulators. The first case would duplicate the measurements made by a capacitor to give a valuable comparison and possibly be a means of checking the calibration of the magnetic probe. It should be far less subject to electrical noise in the environment than the capacitor method because a good vacuum, necessary to prevent breakdown for the capacitor, would not be required. It is in the latter two cases where this technique should find its greatest application. This probe offers the possibility of studying internal flow with a minimal hydrodynamic perturbation. Plane-wave symmetry can be maintained in the experiment. The magnetic fields can be made axially symmetric and, for the field strengths used, will leave the flow unaffected. A 1-mil foil of copper is adequate to screen out fields due to motions of a driver plate on the time scale required, but thinner foils can be used if required. A major asset of this type of experiment is that the sample assembly is uncomplicated. No leads or circuitry are required through the shock front. The particle velocity of the foil can be followed for a considerable time and through a fairly complicated history of wave interactions for various kinds of assemblies. It might be possible to use the capacitor in a similar arrangement by using an electric field to probe through the insulator instead of a magnetic field; however, the change in the dielectric constant of the shocked material can give rise to signals as large as that due to the particle velocity of the foil. It would only take the slightest amount of conductivity produced by the shock in the insulator to give the illusion of the metal foil traveling at the shock velocity if one were to use the capacitor. By contrast, in the magnetic case, excluding ferromagnetic materials, the magnetic permeability differs from one by parts per ten thousand, even for shocked materials. The insensitivity of the magnetic field to a slight conductivity, and the great range of conductivities that exist, permits this probe to view the intervening insulator as a vacuum. It might eventually be interesting to use the two methods in tandem to study the conductivity and dielectric constants of shocked media.

The chief difficulty of using magnetic fields in this fashion is calibration. Unlike the capacitor, whose signal depends on the position of the conducting surface that can be calibrated statically, the magnetic probe uses an effect (the change of flux through a test loop where the flux depends on the past history of the velocity) that directly measures the velocity of the surface and thus cannot be calibrated statically. All that the magnetic probe sees, again excluding ferromagnetism, is the conductivities of the media and the instantaneous and past-time geometries of the good conductors in the immediate vicinity of the experiment. The appropriate governing equations, however, being linear, are amenable to solution. Alternately, a known particle velocity can be used to calibrate a standard assembly, which in some cases is self-calibrating. A known initial jump in particle velocity can calibrate subsequent variations, provided they are early enough so that diffusion and changes in field geometry due to motion do not disturb too severely the correlation between velocity and voltage output. It is clear that one must be concerned with all good conductors in the vicinity of the experiment that will affect the magnetic field. To a certain extent, this will depend on the source of the magnetic field such as pulsed coil, a dc coil, or a permanent magnet. Unwanted ferromagnetic materials must be carefully excluded from the vicinity of the experiment. Given some method of calibration, it should then be possible to obtain $u_p (x_{foil}, t)$ in many diverse situations. In particular, shock-wave structure and the associated particle-velocity flows in earth rocks and minerals should be measurable in a large variety of situations.

The explosive-driver system for the first series of experiments with the axial probe was a P-80, 4 in. of Composition B, and a 0.5-in. base plate of 2024 aluminum. Pick-up coils were constructed by winding wire around pieces of stock Micarta tubing. Leads from the coil were brought to a 93 Ω-μ dot connector inserted into the end of the tubing. Various arrangements of permanent magnets and pulsed coils were tried as sources for the field. Some pick-up coils and three types of permanent magnet arrangements are shown in Fig. 9. Type B, where the coil is in the region where the magnetic field is flaring out and where the

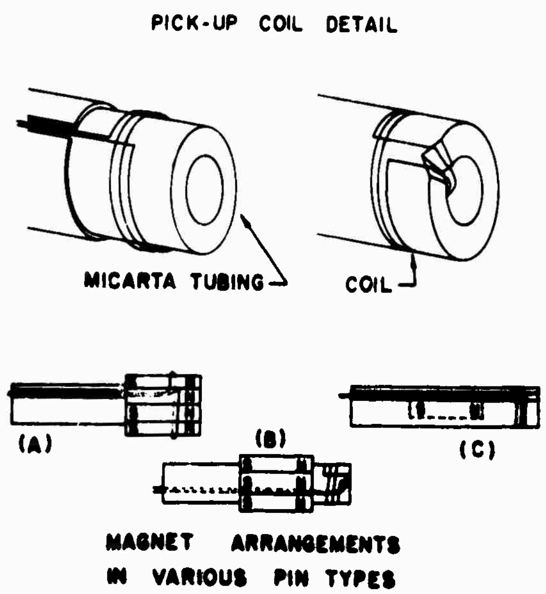


Fig. 9. Pick-up coils and magnetic pins. Three-turn coils of No. 36 HF wire were wound on stock Micarta tubing (usually 2 in. long by 3/8 in. o.d. by 1/4 in. i.d.). Pin type A consisted of a hexagonal close-packed arrangement of seven small Alnico bar magnets (7/8 in. long by 1/4 in. by 1/8 in.) glued to a Micarta rod. One of the magnets in the external ring was wrapped with insulation to break up a conducting circuit that would have prevented the flux from changing in the pick-up loop. Type B had six small Alnico bar magnets taped around the outside of the Micarta tubing. The leads from the coil were brought back inside the tubing. Type C had a small 1/4-in. o.d. cylindrical magnet inside the tubing and leads were brought back on the outer surface.

diameter is comparable to the physical extent of the end of the magnet, was found to have twice as great a signal as the other two types.

One early experimental arrangement consisted of 2024 driver, 0.25 in. of air + 0.25 in. of Plexiglas + a magnetic pin, roughly of the C type, resting on the surface of the Plexiglas. The time measurement afforded by the interval from the start of the signal to where the signal decreased at the interaction of the 2024 aluminum and Plexiglas and the known thickness of the air gap yielded an average free-surface velocity for the driver plate of 3.18 mm/μsec. The ratio of the signal before the interaction to its value after interaction was 1.39, which gives a particle velocity of 3.18/1.39 = 2.3 mm/μsec in the Lucite. These numbers are in satisfactory agreement with other measurements (3.24 and 2.38 mm/μsec). This free-surface velocity for the driver plate, and the signals from the three types of pins, imply initial sensitivities for the pins of 0.026, 0.055, and 0.0096 V/mm/μsec, respectively. This is by no means an exhaustive study of possible geometric configurations but the general rule that sensitivity will be greatest when the coil is placed where the flux lines have the greatest chance to move will always be true. For these configurations, the sensitivity increases with distance traversed by the driver plate.

The experimental configuration shown in Fig. 10 produced the record shown in Fig. 11. We attempted to use the embedded foil idea to study the structure of the particle velocity in the glass. The aluminized surface of the mirrors, thickness unknown, was not sufficiently conducting to pin the lines. Both pins started recording as soon as the 2024 free surface started to move. When the shock arrives at the aluminized surfaces, about 1.2 μsec after the 2024 surface starts to move, a small blip should occur in the upper trace.

A signal of the expected shape occurs at about the right time on the upper trace in Fig. 11 about 1 cm from the right side of the grid. The time to this signal, 1.19 μsec, yields a wave velocity of 4.95 mm/μsec through the 0.232 in. of glass. This is in fair agreement with Wackerle's[9] bulk-wave velocity in fused silica, but corrected for the density difference (5.2 mm/μsec x (2.204 g/cm³/2.51 g/cm³)$^{1/2}$ = 4.87 mm/μsec). Most of the features in these probe signals are understood.

In the next experiment, the aluminized surfaces were replaced with a 1-mil copper foil. A

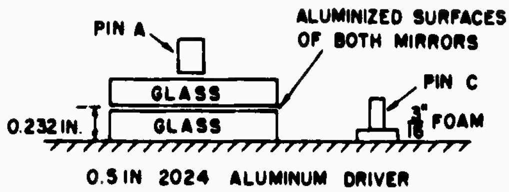


Fig. 10. Experimental assembly using glass mirrors. Pin types A and C were located as shown in the drawing. Pin C, whose purpose is to record wave arrival at the 2024 surface, was supported by a layer of light-density foam. Pin A, intended for measuring the particle velocity at the aluminized interface, was placed on top of the 4 in. by 6 in. mirrors.

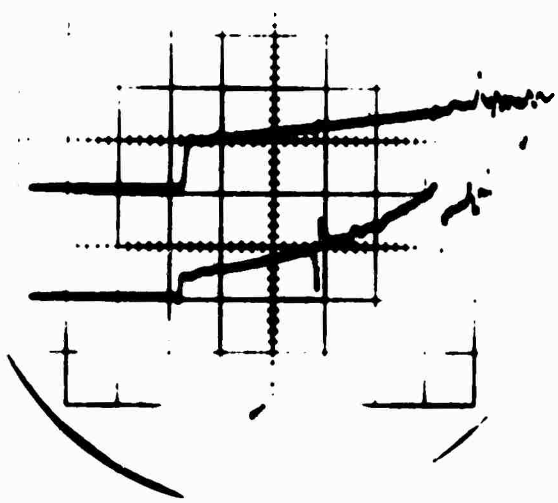


Fig. 11. Probe records from the assembly in in Fig. 10. A dual-beam Tektronix 556 oscilloscope was used. Probes were connected to the 93 Ω input impedances of the scopes by 50 ft lengths of RG-71 B/U cable. Pin A is the upper trace. It has a vertical voltage of 0.1 V/cm and a sweep time of 0.2 μsec/cm. The initial 0.09-V step with its rise time of 0.04 μsec is caused by motion of the 2024 free surface. Most of the rise time is a consequence of diffusion of the field lines through the aluminized surfaces. The next wiggle is about right for a reflection through the cable of the initial square wave (round trip time is 0.1 μsec). The source of the signal occurring 0.5 μsec from the beginning of both traces is unknown. Its most probable cause is a jet forming at the right angle between the 2024 free surface and the side of the mirror. Material from this jet could disturb the field in probe C (lower trace, 0.05 V/cm) that could result in the excursion in the signal shown. The corresponding wiggle in the A trace is there because the A circuit is not shielded except by distance from effects of fluctuations in the field of the C probe. The timing for this signal would indicate a jet velocity of 8 to 9 mm/μsec. A sudden drop in signal of the C-trace at 1.03 μsec after the square wave is caused by arrival of the shock wave in the foam at the coil in the C-probe (U_s indicated in the foam is 4.6 mm/μsec). In another record of the same event in which a longer signal time was recorded, the C-trace subsequently varied wildly and irregularly due to motion imparted to the coil and magnet. This showed up as a heightened noise level in the A trace, a level, however, which remained less than half the amplitude of the blip signaling the arrival of the wave at the aluminized surfaces of the mirrors.

pulsed coil replaced the permanent magnet as the magnetic field source. This source coil and its associated pick-up coil, which were placed on the top of the 0.232-in. glass - foil - 0.235-in. glass sandwich, is shown in Fig. 12. The source coil and its power source, a capacitor bank, form an LRC circuit with L = 10.4 μh, C = 29 μf, and an attenuation factor from the resistance of about 0.71. Peak current, occurring at the quarter-period time of 27 μsec, was 1.34 kA with a charging voltage of 1.13 kV. The five turns of the source coil yielded 6.69 kA turns to produce the source field. With this current and the positions of the source loops, pick-up loops, and the foil, an initial sensitivity of 0.90 V/mm/μsec was calculated. However, because of the unknown amount of diffusion of the field from the pulsed coil into the copper foil and 2024 base plate, this must be regarded as a very rough number, and a second

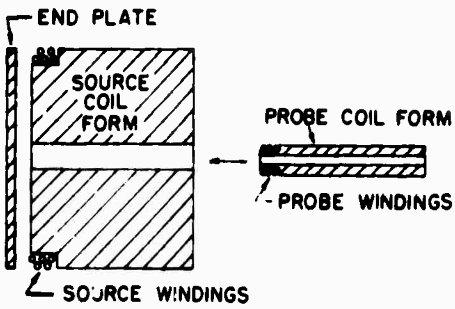


Fig. 12. Source coil and its associated pick-up coil in cross section. Five turns of No. 15 HF wire on a 1.478 in. diam by 0.185 in. long neck, turned down from the 1.728 in. diam solid Micarta stock, formed the source coil. Return leads were brought back through a 1/8 in. by 1/16 in. groove on the outside of the form. The probe coil form is made from 1/4 in. o.d. by 1/8 in. i.d. Micarta stock tubing. Fifteen mils were turned off one end to make room for the three-turn probe coil when the form is inserted in the 1/4-in. hole in the source coil form. Return leads from the probe come back through the center. The assembly is glued down to an end plate, 1/16 in. thick by 1.728-in. diam disk of Micarta, and the entire form is placed on the sample assembly.

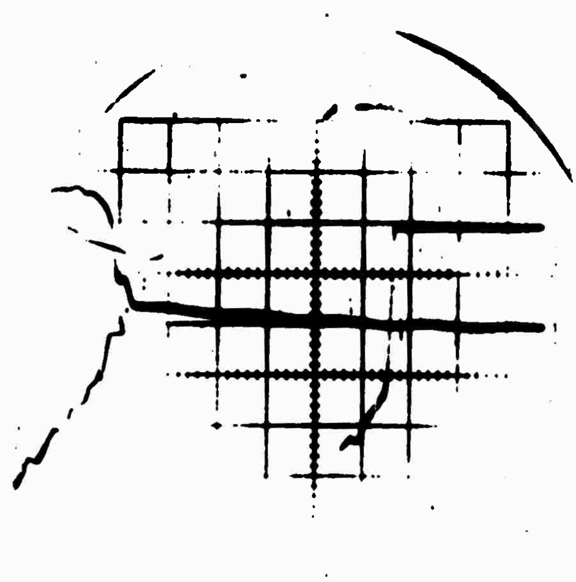


Fig. 13. Probe record from a glass-copper foil-glass assembly. Time increases to the left. The upper trace (voltage deflection downward) is from a type C pin, and gives wave arrival at the 2024 surface. The lower trace is the signal corresponding to the particle velocity of the copper foil.

shot for calibration purposes was fired. (A short account of this type of calculation is given by Hayes and Fritz.[10] A full description will be given in a future report.) The resulting record is shown in Fig. 13. A marker pin (upper trace) served to establish time of initial free-surface motion. The base line of the foil particle-velocity trace shows a slight ringing and a gradual drift, which indicates a residual time variation in the source field from the pulsed coil. The smallness of the drift indicates that the experiment occurred quite close to the peak value of the current through the source coil. Finally, the two-wave structure characteristic of any substance with a substantial amount of amorphous silica present is observed. Use of the sensitivity calculated above gives particle velocities of 0.29 and 1.21 mm/μsec for these two steps. The measured shock velocities for the two steps were 5.44 and 5.14 mm/μsec, respectively. A calibration shot, with a 0.205-in. Plexiglas, 1-mil copper foil, 0.175-in. Plexiglas sandwich, was done with a similar pulsed-coil pick-up coil assembly. This record is shown in Fig. 14. The calculated sensitivity for this particular pulsed-coil assembly would indicate a particle velocity of 1.28 mm/μsec in the Plexiglas. However, the measured shock velocity, 6.26 mm/μsec, and the LASL Group GMX-6 Hugoniot for Plexiglas would imply a particle velocity of 2.20 mm/μsec. This latter number is in agreement with the earlier experiment quoted previously, although that number was taken after the 2024 had a free run.

The calculated sensitivity assumes a field from the pulsed coil that would exist after a very

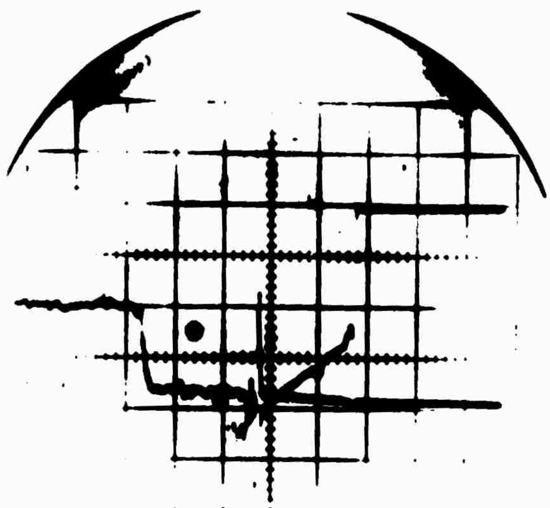


Fig. 14. Probe record from a Plexiglas-copper foil-Plexiglas sample assembly. The general features are the same as in Fig. 13. This record shows a disturbance similar to the one occurring in the record in Fig. 11. The cause is probably the same.

long time at a steady current. Although the 27-μsec quarter period time of the capacitor discharge circuit is adequate to allow most of the field to diffuse through the 1-mil copper foil, it is not long enough to allow the field to reach an equilibrium value in the thick 2024 aluminum base plate. This reduction in responding field can easily account for the voltage signals being smaller than expected. If we use the ratio of the correct Plexiglas particle velocity to the measured one to correct the particle-velocity signals from the glass experiment (this ratio should only depend on the geometry of the pulsed coil with respect to the 2024 base plate), we obtain 0.50 and 2.08 mm/μsec for the two particle-velocity steps in the glass. These latter numbers are in much closer agreement with the expected steps in such a material. Although a direct comparison cannot be made because this glass has a density of 2.51 g/cm^3, the corresponding steps in fused silica from such a driving system would be ~ 0.8 mm/μsec and 2.10 mm/μsec.

The axial probe offers much the same possibilities as the U-probe. Sample assembly is simpler; however, a larger sample is usually required. No connections are necessary through the free surface, therefore the axial probe can look at wave motions influenced by signals propagating back into the sample from the free surface. Figure 15 shows the axial probe monitoring a particle velocity for about 7 μsec after the wave has emerged from the free surface.

Several points may be noted about these initial experiments.

A. Probably the best source for the axial probe field is a highly symmetrical, good quality cylindrical permanent magnet. Such a symmetric field can be more easily obtained from a coil, but the problem of the long time required to let the field diffuse into a calculable equilibrium value outweighs the advantage of having a calculable field. A great advantage of the permanent magnet is that it is passive; it does not require a power supply. Some work with such magnets, measuring the motion of foils in detonating explosives, has already been done.[10]

B. If permanent magnets are used, a method of routine calibration and characterization of the field of the magnets must be devised to permit the quantitative reduction of axial probe voltage records to the corresponding particle velocity. The availability of commercial Hall probes simplifies the problem of measuring the magnetic field. A device for producing coordinates of the Hall probe with respect to the magnet should be constructed. Coordinates and field values should be digitized and automatically recorded by electronic data-processing equipment. Such a setup also would be useful for measuring fields for the U-probe.

C. Some consideration should be ...

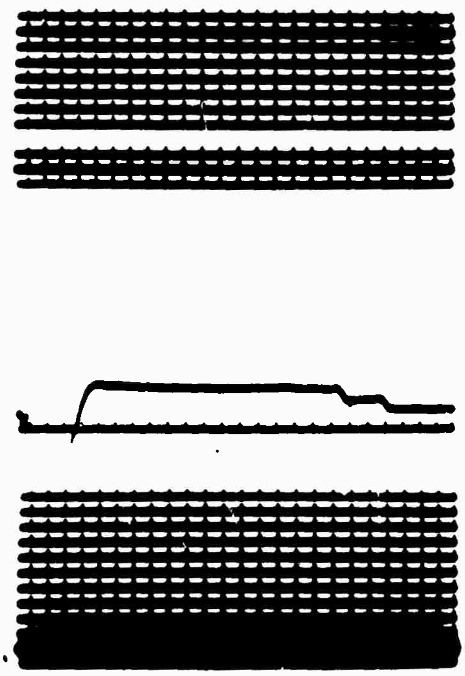


Fig. 15. Probe record from a fused silica-copper foil-fused silica assembly. The particle velocity was produced by impacting a fused silica face [illegible] warhead driven by a 3-in.-diam gun. Time increases to the left and the time marks are 0.5 µsec markers. The signal was produced by a type B magnetic probe. The particle velocity pr[illegible] was only 0.2 mm/µsec, insufficient to [illegible] a transition. The record shows the arrival of the (essentially) elastic wave and the increase in particle velocity associated with the rarefaction coming back from the front free surface. Probe destruction occurs at the end of the record when the free surface impacts the probe.

pick-up coil design. Time resolution of the order of a nanosecond is possible with a single-turn coil. Increased signal (proportional to N, the number of coil turns) can be gained for a sacrifice in rise time (proportional to N^2).

D. Given an accurately known geometry and a convenient mathematical description of the source field, a numerical code should be written that has the capability of extracting the particle velocity of the foil from the linear integral equations governing the motion of the magnetic field. The known magnetic field will then permit an absolute determination of the particle velocity of the foil.

E. Consideration should be given to how small one can construct a probe and still have an adequate signal-to-noise ratio.

Studies [illegible] and with the axial probe should continue.

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